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A 16-year record of eolian dust in Southern Nevada and California, USA: Controls on dust generation and accumulation

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Abstract

An ongoing project monitors modern dust accumulation in the arid southwestern United States to (1) determine the rate and composition of dust inputs to soils and (2) relate dust accumulation to weather patterns to help predict the effects of climate change on dust production and accumulation. The 16-year records of 35 dust-trap sites in the eastern Mojave Desert and southern Great Basin reveal how generation and accumulation of dust, including the silt-clay, carbonate, and soluble-salt fractions, is affected by the amount and seasonal distribution of rainfall and the behavior of different source types (alluvium, dry playas, and wet playas).

Accumulation rates (fluxes) of the silt-clay fraction of dust, including carbonates, range from about 2–20 $g/m^2/yr$. Average rates are higher in the southern part of the study area (south of latitude 36.5°N) and annually fluctuate over a larger range than rates in the northern part of the area. Sites throughout the study area show peaks in dust flux in the 1984–1985 sampling period and again in 1997–1999; northern sites also show increased flux in 1987–1988 and southern sites in 1989–1991. These peaks of dust flux correspond with both La Nina (dry) conditions and with strong El Nino (wet) periods. The accumulation rates of different components of mineral dusts fluctuate differently. For example, soluble-salt flux increases in 1987–1988, coincident with a moderate El Nino event, and increases very strongly in 1997–1999, overlapping with a strong El Nino event. Both of these high-rainfall winters were preceded and accompanied by strong summer rains. In contrast, little or no change in soluble-salt flux occurred during other periods of high winter rainfall but little summer rain, e.g. 1992–1995. The differences between northern vs. southern sites and between sites with playa dust sources vs. alluvial dust sources indicate that regional differences in the response of precipitation and vegetation growth to ENSO influence and differences in the response of source types control dust production and accumulation.

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A major factor is the hydrologic condition of surface sediments. The silt-clay and soluble-salt fluxes increased during the El Nino events of 1987–1988 and 1997–1998 at sites close to "wet" playas with shallow depths to groundwater (<10 m), consistent with the concept that active evaporative concentration of salts disrupts surface crusts and increases the susceptibility of surface sediment to deflation. The silt-clay flux also increased during drought periods (1989–1991, 1995–1997) at sites downwind of alluvial sources and "dry" playas with deeper groundwater (<10 m). These increases are probably related to the die-off of drought-stressed vegetation on alluvial sediments, and in some cases to local runoff events that deliver fresh sediment to playa margins and distal portions of alluvial fans.

Keywords: Dust; Wind erosion; Dust source; Playa; Ground water; ENSO

1. Introduction

The source, entrainment, transportation, and deposition of eolian dust are topics of critical interest to the scientific community. Atmospheric dust affects global climate through its effects on radiation (Tegen, 2003) and serves as a primary source of nutrients to soils and aquatic ecosystems (e.g. Swap et al., 1992; Boyd et al., 2004; Okin et al., 2004). Dust storms impact economies and societies by obscuring visibility, causing health problems, and stripping agricultural soils. Global and regional models of dust emission are widely used to understand the history of emissions and to forecast future effects of natural and human-induced climate change and land use on dust production (Ginoux et al., 2001; Mahowald and Luo, 2003; Tegen, 2003; Tegen et al., 2004). Only a handful of long-term monitoring (>10 yr) studies of dust emission or deposition are available to test model accuracy. The models incorporate significant uncertainties in the response of dust-producing areas to seasonal, annual, and long-term changes in climate, because in many cases the behavior of dust sources is poorly understood. Prospero et al. (2002) used global satellite observations to suggest that most major dust sources are in areas of previous or ongoing deposition by alluvial systems and ephemeral lakes. Bullard and Livingstone (2002) noted the sensitivity of interactions between eolian and fluvial systems due to changes in moisture availability and sediment supply. Many studies showed a close correspondence of drought years to increased dust generation (summarized in Pye, 1987), whereas others noted that delivery of fresh sediment by storms yields increased dust flux (e.g. McTainsh et al., 1999). At least two studies found that in some cases, dust flux increases in wet years (Reheis and Kihl, 1995; Okin and Reheis, 2002). To address these complexities, long-term dust monitoring at sites chosen to show the different responses of dust sources to climatic events is required.

This report relates composition and accumulation rate of eolian dust in dust-emitting source areas of southern Nevada and California to annual precipitation patterns from 1984 to 2000 and to the hydrogeologic setting of nearby dust sources. There are very few studies of the behavior of different types of dust sources relative to climate parameters, a notable exception being that of Prospero and Lamb (2003) on a 30-year record of African drought and dust transport to the Caribbean. No previous studies have addressed the behavior of different physical or chemical fractions that typically compose deposited dust with respect to source and climate.

2. Materials and methods

2.1. Sampling and analysis of dust

Sample sites were originally chosen based on proximity to soil-study locations and weather stations and on the need to answer specific questions about the relations of dust to local sources, distance from source, and climate (Fig. 1). For details on trap construction, sample collection, and analytical procedures, see Reheis and Kihl (1995) and Reheis (1999, 2003). Briefly, the trap consists of a coated angel-food cake pan mounted on a post about 2 m above the ground. Glass marbles rest on metal mesh that is fitted into the pan so that it rests 3–4 cm below the rim. Thus, the samples integrate wet and dry deposition during the

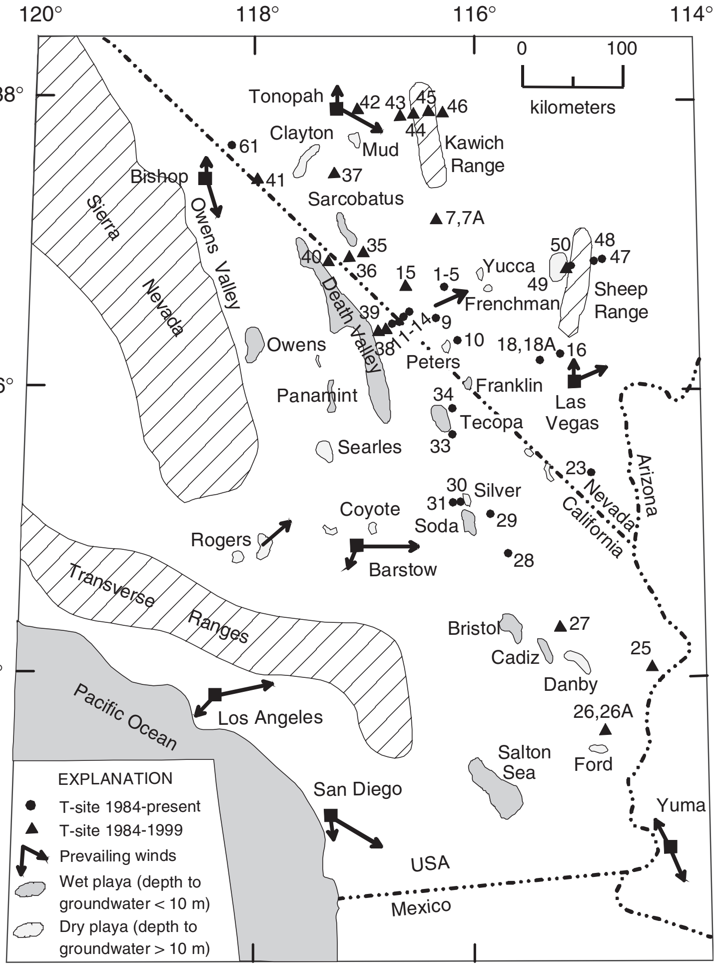


Fig. 1. Map of California-Nevada portion of study area showing dust trap sites, playas (not all shown), and prevailing winds. Length of arrow is proportional to frequency and strength of annual winds. Although proximity to wet and dry playas is indicated, local topography (intervening mountains not shown, for example) dictate whether a site is assigned to a principal dust source of alluvium, wet playa, or dry playa.

period of accumulation. The database for any one site contains gaps depending on how far each sample could be stretched through the analytical cascade. In some cases, samples from different years at the same site or adjacent sites were combined to obtain enough material for measuring grain size (Table 3 in Reheis, 2003). Because of these changes, data for the $<20\,\mu m$ and $<10\,\mu m$ particle sizes are insufficient to allow comprehensive statistical analyses. Thus, this paper will restrict discussion to the silt-plus-clay ($<53\,\mu m$) fraction, hereafter referred to as "silt-clay", and the clay ($<2\,\mu m$) fraction.

The change to coulometric measurement of inorganic carbon, measured using a Chittick gasometric apparatus until 1997, coincided with an apparent drop in dust carbonate content. Measurement of sample splits using coulometry and the Chittick technique yielded comparable results for samples that contained $>15\%$ $CaCO_3$ but for lower concentrations yielded amounts by coulometry that were two-thirds to less than one-third those measured by Chittick. Thus, the "abrupt" change in carbonate contents of dust is most likely a result of measurement technique and statistical analyses on carbonate flux omit values for 1997–2000.

Caution must be used when interpreting the dust data from this study and comparing it to other studies (Goossens, 2005). Not all dry deposition that occurs at a site may be retained in a sample, because dry dust that remains on the top layer of marbles can be deflated from the trap. The round pans do not impose a bias on deposition efficiency related to wind direction, but they are not aerodynamic and will create local turbulence that may reduce accumulation amounts. In addition, data from several sites with paired traps, one protected by a meteorological wind-baffle (T3 compared to T1, T2, T4, and T5; T7A vs. T7; T18A vs. T18; T26A vs. T26) indicate that the true rate of dust accumulation at sites with low scrubby vegetation may be 25–40% greater than measured (Reheis and Kihl, 1995).

2.2. Dust sources

Many published studies of natural desert dust sources (excluding anthropogenic disturbance) and dust deposition have found that dust is generated from both alluvial and playa sources (e.g. Pye, 1987; Reheis and Kihl, 1995; McTainsh et al., 1999). However, virtually no studies have addressed different playa types with respect to dust production. Studies on playas and ephemeral lakes document large changes to the structure and composition of playa surfaces caused by flooding and by depth to groundwater (e.g. Snyder, 1962; Teller and Last, 1990; Rosen, 1994); these changes may play integral roles in the susceptibility of playa surfaces to wind erosion (R. Forester, 2004, US Geol. Survey, written commun.).

Dust trap sites are assigned to different primary dust sources depending on what type of source is dominant within 20 km upwind of a site. If both playa and alluvial-fan deposits are present upwind, the site is assigned a primary playa source even though alluvial fan deposits may be more areally extensive. Because the hydrogeologic conditions of playas may be important to dust generation and downwind deposition (Wood and Sanford, 1995), the playas are subdivided based on depth to groundwater and surface characteristics using published (Winograd and Thordarson, 1975; Bedinger et al., 1984; Langer et al., 1984) and internet (http://nwis.waterdata.usgs.gov/usa/nwis/gwlevels) sources of information. Playas are identified in this study as "wet playas" with a groundwater depth less than about 10 m or where known from field observations to be characterized periodically by puffy, salty sediment at the surface. Playas are identified as "dry playas" with a groundwater depth greater than about 10 m or were known to be characterized mainly by hard-packed, silt-clay-dominated surfaces.

2.3. Climatic data

Mean monthly precipitation data for 1982 to 2000 for weather stations in southern Nevada and California (source is National Climatic Data Center) near dust-trap sites were used to calculate the yearly precipitation (YP, Appendix A, Table A.1) during the periods of sample accumulation, generally from October through September of the following year. To examine the influence of unusual weather events on dust accumulation, monthly precipitation values at each site were compared to the mean annual precipitation (MAP, precipitation normals, 1961–1990) of the station. If precipitation in any one month during the winter and early spring (November–April) equaled or exceeded one-third of the MAP, the sum of precipitation during consecutive "unusual" months is designated as a winter precipitation event (WE, Appendix A). If precipitation in any one month during the summer and early fall (June–October) equaled or exceeded one-half of the MAP, the sum of precipitation during one or more "unusual" months is designated as a summer precipitation event (SE, Appendix A). Seasons with no unusual precipitation values are assigned a value of 0. Because dust traps are not located at weather stations, the YP and WE and SE at most sites were estimated by averaging the values from two to four of the closest stations; however, rainfall data from only one station were used at some remote sites.

2.4. Statistical analyses

Dust flux data from Reheis (2003) were used in the statistical analyses. In this database, the silt-clay and clay fluxes include carbonate and exclude soluble salts. Limited data on carbonate contents of sand vs. silt-clay fractions of dust samples suggest that about two thirds of the carbonate resides in the silt-clay fraction, but the contents are quite variable (30–90%). To estimate the silt-clay fluxes excluding carbonate, two-thirds of the total carbonate in a sample was subtracted from the total. Statistical analyses performed using the two different datasets (with and without estimated carbonate amounts, Table 1) show little difference in relations of fluxes with climate variables. Thus, the discussion mainly focuses on the measured silt-clay and clay fractions including carbonate.

Several types of statistical analyses were performed to investigate the relations among dust and climate properties. Tests of normality showed that populations of the three primary flux variables (silt-clay + carbonate, carbonate, and soluble salt) are normally distributed. However, these variables are co-dependent (i.e. when total dust accumulation increases, flux rates of all components also increase). In addition, all properties could not be measured on every sample, yielding a dataset with many missing values. Thus, two related approaches were used to determine the influence of climate on dust accumulation. (1) Precipitation values and mean annual fluxes were compared using simple linear regression on dust flux values and on logarithms of these values. Both approaches yielded statistically significant correlations, but most of the logarithmic regressions gave slightly higher correlation coefficients. To simplify the discussion, only the logarithmic correlations are presented. (2) Categories of precipitation amounts (yearly precipitation—YP, winter event—WE, and summer event—SE, and the previous year's values, previous yearly precipitation—PYP, previous winter event—PWE, previous summer event—PSE) for the sample sites were compared to annual fluxes of dust components using non-parametric

Table 1
Correlations of climate variables with log dust flux

		<50 μm+carb.	<50 μm flux	<2 μm+carb.	Carb. flux	Salt flux	YP	PYP	WE	SE	PWE	PSE
Correlations using all data												
Pearson's *r*	<50 μm+carb.	1	**0.95**	**0.70**	**0.43**	**0.52**	*0.15*	x	x	x	x	x
N		226	215	226	149	215	224	x	x	x	x	x
Pearson's *r*	<50 μm flux	—	1.00	**0.69**	**0.33**	**0.57**	*0.18*	x	x	x	x	x
N		—	215	215	149	204	213	x	x	x	x	x
Pearson's *r*	<2 μm+carb.	—	—	1	**0.29**	**0.33**	x	x	x	*0.27*	**−0.42**	**0.42**
N		—	—	226	149	215	x	x	x	55	103	67
Pearson's *r*	Carb. flux	—	—	—	1.00	**0.32**	*−0.16*	−0.14	x	x	−0.21	x
N		—	—	—	155	144	154	155	x	x	67	x
Pearson's *r*	Salt flux	—	—	—	—	1.00	**0.37**	x	x	x	x	x
N		—	—	—	—	223	221	x	x	x	x	x
Correlations by region												
Northern sites												
Pearson's *r*	<50 μm+carb.	1	**0.95**	**0.68**	**0.42**	**0.51**	*0.21*	−0.16	x	x	x	x
N		152	146	152	96	143	151	152	x	x	x	x
Pearson's r	<50 μm flux	—	1.00	**0.66**	**0.26**	**0.59**	**0.23**	x	x	x	x	x
N		—	146	146	96	137	145	x	x	x	x	x
Pearson's r	<2 μm+carb.	—	—	1	*0.23*	**0.24**	x	x	x	**0.46**	**−0.40**	**0.56**
N		—	—	153	96	143	x	x	x	38	67	47
Pearson's r	Carb. flux	—	—	—	1.00	**0.30**	−0.16	x	x	**0.54**	x	x
N		—	—	—	101	92	100	x	x	22	x	x
Pearson's r	Salt flux	—	—	—	—	1.00	**0.40**	x	x	x	x	x
N		—	—	—	—	148	147	x	x	x	x	x
Southern sites												
Pearson's r	<50 μm+carb.	1	**0.91**	**0.72**	**0.68**	**0.48**	x	−0.19	x	x	−0.30	x
N		74	69	74	53	72	x	73	x	x	36	x
Pearson's r	<50 μm flux	—	1.00	**0.72**	**0.66**	**0.52**	x	−0.20	x	x	*−0.44*	x
N		—	69	69	53	67	x	68	x	x	34	x
Pearson's r	<2 μm+carb.	—	—	1	**0.50**	**0.48**	x	*−0.25*	x	x	**−0.55**	x
N		—	—	74	53	72	x	73	x	x	36	x
Pearson's r	Carb. flux	—	—	—	1.00	**0.42**	x	*−0.30*	x	x	x	x
N		—	—	—	54	52	x	54	x	x	x	x
Pearson's r	Salt flux	—	—	—	—	1.00	**0.32**	**−0.34**	x	x	**−0.46**	x
N		—	—	—	—	75	74	74	x	x	36	x

Correlations by source type												
Sites downwind of mainly alluvial sources												
Pearson's r	< 50 um + carb.	1	**0.95**	**0.68**	**0.54**	**0.47**	x	x	x	x	x	x
N		128	122	128	87	121	x	x	x	x	x	x
Pearson's r	< 50 um flux	—	1.00	**0.67**	**0.43**	**0.50**	x	x	x	x	x	x
N		—	122	122	87	115	x	x	x	x	x	x
Pearson's r	< 2 um + carb.	—	—	1	**0.35**	**0.31**	x	x	x	x	*−0.41*	**0.47**
N		—	—	129	87	121	x	x	x	x	58	40
Pearson's r	Carb. flux	—	—	—	1.00	*0.38*	*−0.22*	*−0.26*	x	x	*−0.37*	x
N		—	—	—	90	83	89	90	x	x	38	x
Pearson's r	Salt flux	—	—	—	—	1.00	**0.30**	x	x	x	x	x
N		—	—	—	—	126	125	x	x	x	x	x
Sites downwind of mainly dry playa sources												
Pearson's r	< 50 um + carb.	1	**0.90**	**0.68**	x	**0.48**	x	*−0.29*	x	x	x	x
N		39	38	39	x	37	x	38	x	x	x	x
Pearson's r	< 50 um flux	—	1.00	**0.67**	x	**0.63**	x	x	x	x	x	x
N		—	38	38	x	36	x	x	x	x	x	x
Pearson's r	< 2 um + carb.	—	—	1	x	*0.36*	x	x	x	x	−0.45	x
N		—	—	74	x	37	x	x	x	x	16	x
Pearson's r	Carb. flux	—	—	—	1.00	x	−0.34	x	x	x	x	x
N		—	—	—	29	x	29	x	x	x	x	x
Pearson's r	Salt flux	—	—	—	—	1.00	*0.37*	x	x	x	−0.46	x
N		—	—	—	—	37	36	x	x	x	16	x
Sites downwind of mainly wet playa sources												
Pearson's r	< 50 μm + carb.	1	**0.99**	**0.74**	**0.61**	**0.63**	**0.45**	x	x	x	x	0.43
N		59	55	59	33	57	59	x	x	x	x	18
Pearson's r	< 50 μm flux	—	1.00	**0.71**	**0.57**	**0.66**	**0.46**	x	x	x	x	x
N		—	55	55	33	53	55	x	x	x	x	x
Pearson's r	< 2 μm + carb.	—	—	1	*0.41*	*0.30*	x	x	x	x	**−0.48**	0.46
N		—	—	74	33	57	x	x	x	x	29	18
Pearson's r	Carb. flux	—	—	—	1.00	**0.55**	x	x	x	x	x	x
N		—	—	—	36	34	x	x	x	x	x	x
Pearson's r	Salt flux	—	—	—	—	1.00	**0.58**	x	x	x	x	x
N		—	—	—	—	60	60	x	x	x	x	x

[YP—precipitation in collection year; WE—winter event (see text); SE—summer event; P—preceding year].
Bold font—Correlation is significant at the 0.01 level (2-tailed).
Italics—Correlation is significant at the 0.05 level (2-tailed).
Normal font—Correlation is significant at the 0.10 level (2-tailed).

statistics. In these analyses, sites were grouped on the basis of region (sites north and south of latitude 36°N) and primary dust source (alluvium, wet playa, and dry playa). For YP and PYP, the categories consist of regular increases in precipitation. For the event variables, the first category is 0 (because some years had no significant rain events during the winter or summer); the other two categories (1 and 2) each represent half the range of values. The populations of dust flux values at all sites with precipitation values within a given category were then compared to the populations of the other categories using the non-parametric Kruskal–Wallis test (three categories) and Mann–Whitney test (two categories). Because these tests do not require normally distributed populations, they provide a robust test of whether populations of different categories (i.e. different rainfall amounts) are statistically different.

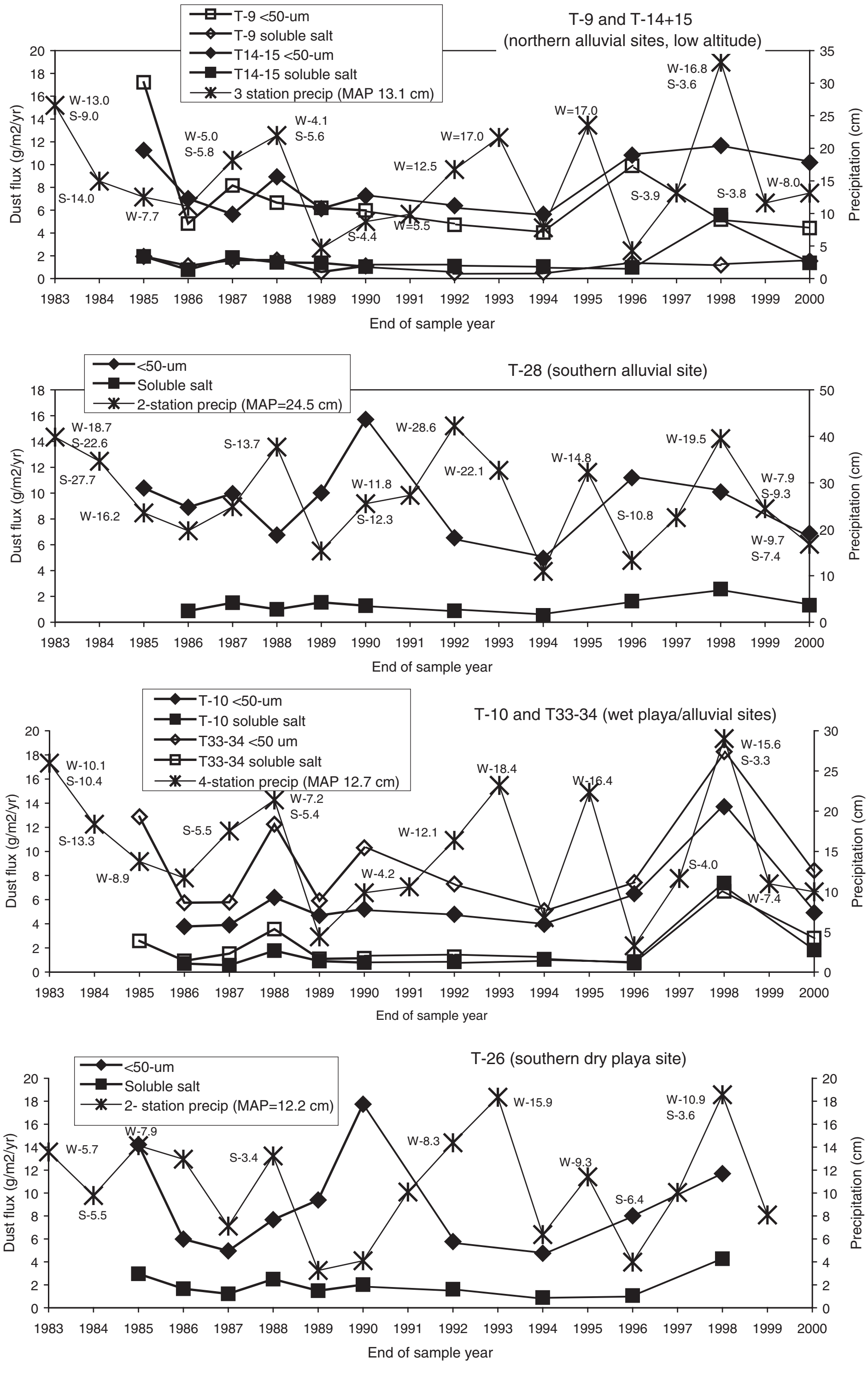
The mixture of collection intervals—1 year for 1984–1989 and 1999–2000, 2 years for 1989–1999—complicated the data analysis. The 2-year samples obviously integrate dust flux over time intervals in which precipitation can vary dramatically. The flux values for 2-year samples were assigned to times corresponding to the middle of the collection period (the end of the first year) for purposes of statistical analyses and plots. An alternate approach is to average the precipitation values for the entire 2 years. Correlation coefficients obtained using this approach (not shown) tend to be lower in value or less significant than those obtained using the middle of the collection period, in part because this method obscures large storm events that may have a very strong influence on dust production. However, some correlations using averages suggest negative relations among dust fluxes and precipitation, and this may reflect the lag time induced by vegetation growth in response to precipitation increases (discussed below).

3. Results

Accumulation rates (fluxes) of the silt-clay fraction including carbonates in the study area range from about 2 to 20 $g/m^2/yr$ (data in Reheis, 2003). Average values for the 16-year record are between 4.5 and 16 $g/m^2/yr$. Average clay fluxes ($<2\,\mu m$ fraction, including carbonates) for the 15-year record are of course smaller, ranging from about 0.8–3.2 $g/m^2/yr$, and at individual sites may vary by as much as a factor of 5. Average carbonate fluxes (1984–1995) are about 0.7–4.0 $g/m^2/yr$. All carbonate-flux values above $\sim 2\,g/m^2/yr$ are from sites located on limestone-dominated alluvial fans, showing the influence of these local dust sources (Reheis and Kihl, 1995). Average soluble-salt fluxes range from about 0.8–2.0 $g/m^2/yr$; yearly salt fluxes at individual sites vary more than do those of the silt-clay and carbonate fractions.

Comparison of the annual variation in silt-clay flux to precipitation at individual study sites suggests that there are two main patterns. (1) Some peaks in dust flux occur during dry years, especially notable after several years of drought at southern sites with alluvial and (or) dry-playa sources (T-28 and T-26, Fig. 2). (2) Some peaks in dust flux occur in the

Fig. 2. Examples of changes in soluble-salt and silt-clay fluxes at selected sites (locations in Fig. 1) with YP. Sample year is approximately October–September. Data points are plotted at the end of each sample year for annual samples, including precipitation values, and in the middle of the sample interval for 2-year samples. Precipitation values are annotated with totals (in cm) of moisture received during one or more exceptionally wet months as compared to normal mean annual precipitation (MAP; see text for description of technique): W, winter event; S, summer event. Precipitation values from Appendix A.


T-9 and T-14+15
(northern alluvial sites, low altitude)
T-9 <50-um
T-9 soluble salt
T14-15 <50-um
T14-15 soluble salt
3 station precip (MAP 13.1 cm)
Dust flux (g/m2/yr)
Precipitation (cm)
End of sample year
W-13.0
S-9.0
S-14.0
W-7.7
W-5.0
S-5.8
W-4.1
S-5.6
S-4.4
W=5.5
W=12.5
W=17.0
W=17.0
S-3.9
W-16.8
S-3.6
S-3.8
W-8.0
T-28 (southern alluvial site)
<50-um
Soluble salt
2-station precip (MAP=24.5 cm)
W-18.7
S-22.6
S-27.7
W-16.2
S-13.7
W-11.8
S-12.3
W-28.6
W-22.1
W-14.8
S-10.8
W-19.5
W-7.9
S-9.3
W-9.7
S-7.4
T-10 and T33-34 (wet playa/alluvial sites)
T-10 <50-um
T-10 soluble salt
T33-34 <50 um
T33-34 soluble salt
4-station precip (MAP 12.7 cm)
W-10.1
S-10.4
S-13.3
W-8.9
S-5.5
W-7.2
S-5.4
W-4.2
W-12.1
W-18.4
W-16.4
S-4.0
W-15.6
S-3.3
W-7.4
T-26 (southern dry playa site)
<50-um
Soluble salt
2- station precip (MAP=12.2 cm)
W-5.7
S-5.5
W-7.9
S-3.4
W-8.3
W-15.9
W-9.3
S-6.4
W-10.9
S-3.6

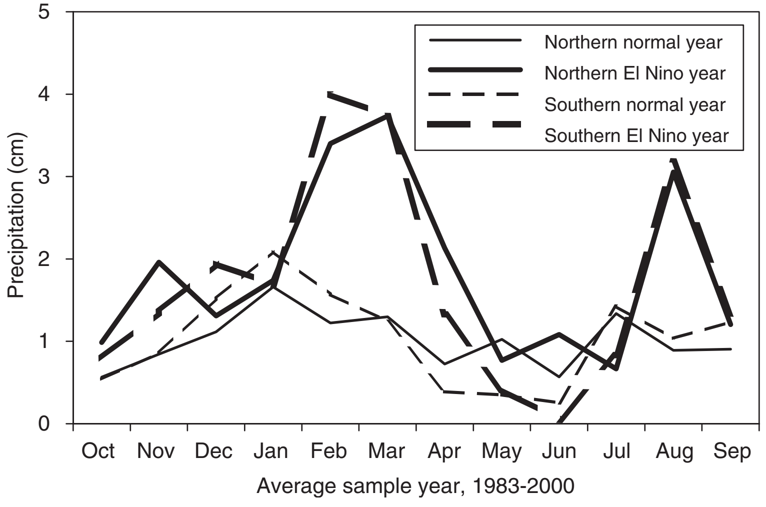


Fig. 3. Monthly average precipitation for El Nino years and "normal" (non-El Nino) years during period of study at weather stations in northern and southern areas.

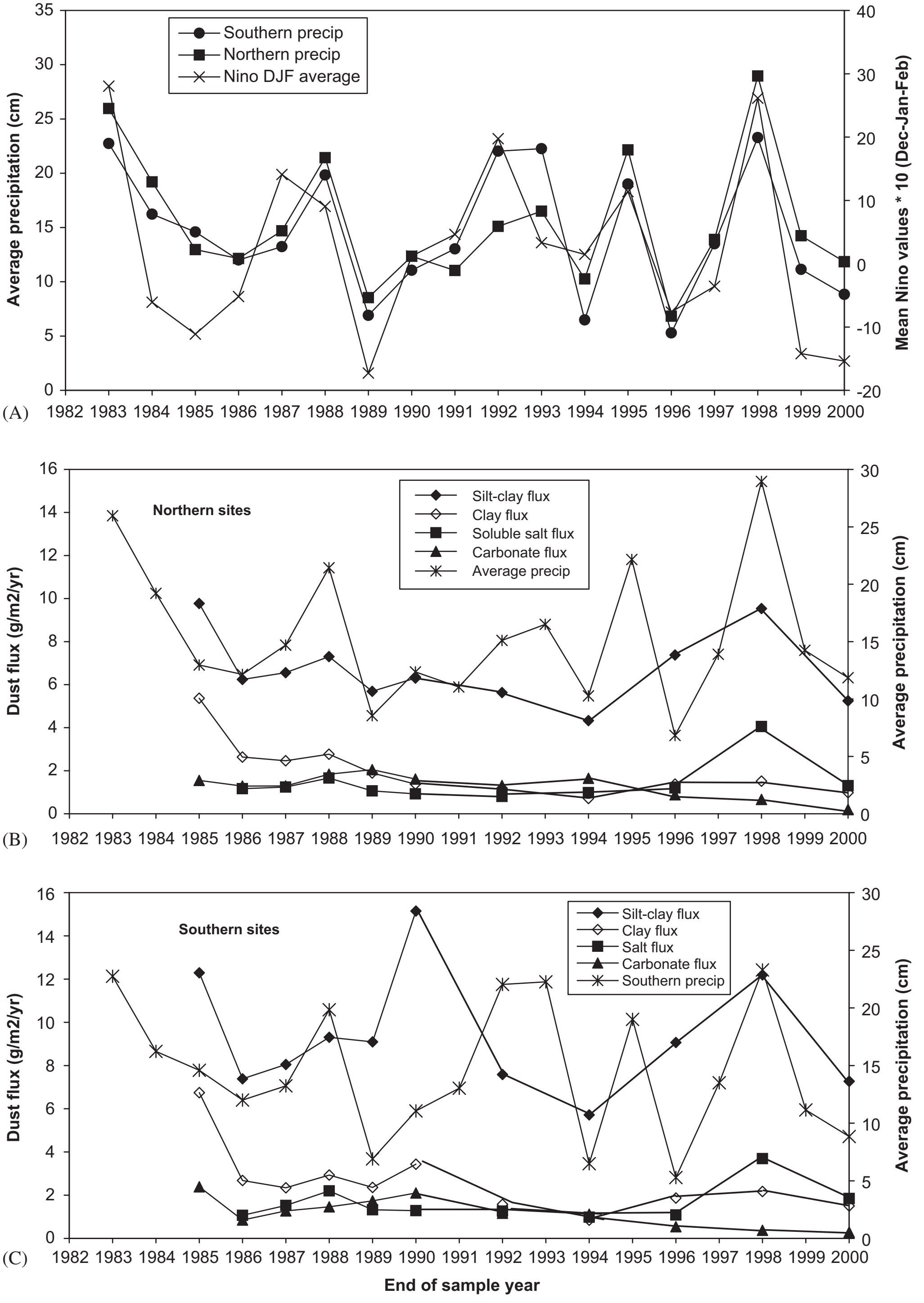
same year as peaks in precipitation or possibly in the following year (for 2-year samples), especially at sites downwind of wet playas (e.g. T-10 and T33–34, Fig. 2). Peaks in soluble-salt flux are highly correlated with wet years, especially those preceded by significant summer rain events. For example, nearly all sites show strong increases in soluble-salt flux during or just after the 1997–1998 El Nino event and many sites near playas show lesser increases in 1987–1988. The soluble salt fluxes available for a few of the 1984–1985 samples also are higher than average, possibly due to strong summer rains in the preceding year or to the large El Nino event of 1982–1983.

Simple regressions of dust flux with climate variables (Table 1) show that the silt-clay and soluble-salt fluxes have weak positive correlations with YP, whereas carbonate flux has a negative correlation with YP, PYP, and previous winter precipitation event (PWE). Clay flux is also negatively correlated with PWE, but it is positively correlated with SE and especially previous summer event (PSE). Salt flux and silt-clay flux are significantly correlated ($r^2 = 0.27$), and carbonate flux is less well correlated to silt-clay flux and to salt flux. These observations suggest that the different components of dust flux reflect differing responses of source types to precipitation events.

3.1. Regional precipitation effects on dust flux

Previous studies have suggested significant effects of El Nino-Southern Oscillation (ENSO) on dust flux (Holcombe et al., 1987; Okin and Reheis, 2002). To examine relations of ENSO to regional precipitation, the averaged weather records at stations north and south of latitude 36.5°N were compared to values from an ENSO index, Nino 3.4

Fig. 4. Average precipitation compared to average fluxes of dust components in northern and southern parts of study area (dividing line at about 36°N latitude, Fig. 1). (A) Average precipitation at all weather stations in northern and southern areas compared to average of December–January–February Nino 3.4 index values. (B) Dust flux and precipitation at northern sites. (C) Dust flux and precipitation at southern sites.


(A)
Southern precip
Northern precip
Nino DJF average
Average precipitation (cm)
Mean Nino values * 10 (Dec-Jan-Feb)
(B)
Northern sites
Silt-clay flux
Clay flux
Soluble salt flux
Carbonate flux
Average precip
Dust flux (g/m2/yr)
Average precipitation (cm)
(C)
Southern sites
Silt-clay flux
Clay flux
Salt flux
Carbonate flux
Southern precip
Dust flux (g/m2/yr)
Average precipitation (cm)
End of sample year

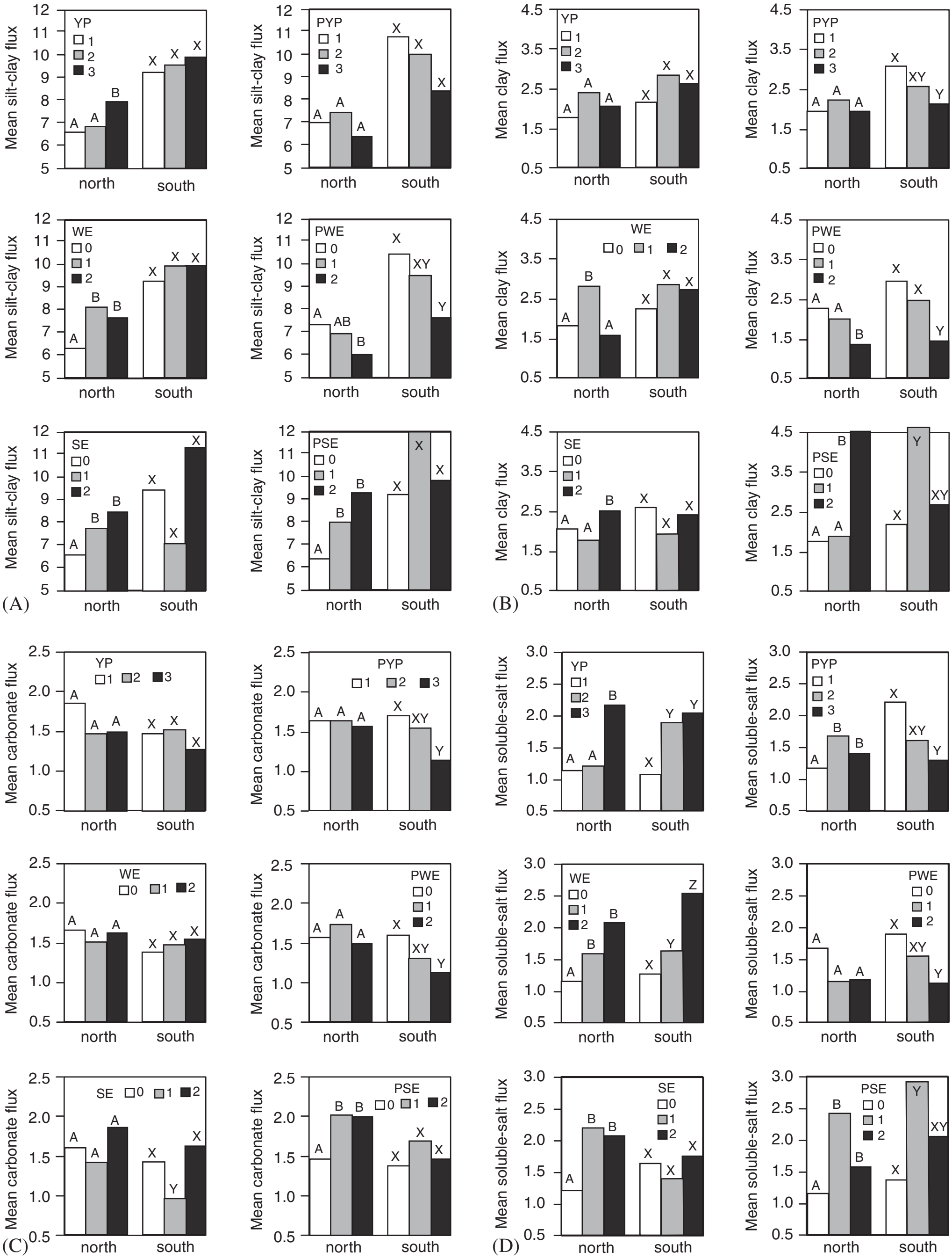
(http://ingrid.ldgo.columbia.edu/), by averaging the index values for December, January, and February of each sample year. This latitude was chosen because it roughly divides sites in the south that were thought to be more directly under the influence of the southerly summer monsoon from those in the north that receive mostly winter and spring moisture from the west and north (French, 1983). In addition, sites in the northern area have higher average altitudes (Reheis, 2003) and, of course, latitudes than sites in the southern area; hence, northern sites should have lower evaporation rates. However, the northern and southern areas during the 16-year study period have similar seasonal distributions of precipitation, with slightly more moisture during the winter (December–March) than in the summer (July–September) and very little moisture at other times in most years (Fig. 3).

Comparison of regional average precipitation to Nino 3.4 values shows that during El Nino years of 1983–2000, precipitation peaked sharply from February to April and again in August (Fig. 3). The only apparent difference is that northern sites received somewhat more precipitation in April, May, and June in "normal" (non-El Nino) years. The average YP closely followed the ENSO cycle in both regions (Fig. 4A), with two exceptions: (1) precipitation peaked in the second year of a moderate, lengthy El Nino event from 1986 to 1988 but not in the first year, and (2) precipitation rose sharply in the southern region during and after a moderate El Nino event in 1991–1992, whereas precipitation in the northern region showed little change. Because the precipitation records are so similar to ENSO records, analyses discussed below compare dust flux directly to the precipitation records.

Comparison of average precipitation and dust flux shows that northern and southern areas respond somewhat differently in dust accumulation (Fig. 4B, C). Average silt-clay fluxes are higher in the southern part of the study area (south of latitude 36.5°N) and fluctuate annually over a larger range (6–16 g/m^2/yr) than those in the northern part of the area (3–9 g/m^2/yr)(data in Reheis, 2003). Sites throughout the study area show peaks in dust flux in the 1984–1985 sampling period and again in 1997–1999; northern sites also show increased flux in the 1987–1988 sampling period and southern sites in 1989–1991. These peaks of dust flux correspond with dry (La Nina) conditions and sometimes with very wet (strong El Nino) periods. Southern sites experienced a peak in silt-clay dust flux in the 1989–1991 sampling period following several years of drought punctuated by a moderate increase in precipitation. In contrast, northern sites had no such increase in dust flux despite a similar precipitation pattern. A succession of weak El Nino-La Nina conditions during 1991–1995 apparently suppressed dust production throughout the study area. Carbonate fluxes seem to follow the silt-clay fluxes in annual variations until 1995, but show little difference between northern and southern areas. Soluble-salt fluxes in the northern and southern areas are similar in overall amount and in annual changes (Fig. 4B, C). Salt fluxes are low and relatively constant during dry and moderately wet periods and increase sharply during or just after years of relatively high rainfall, including 1987–1988 and especially the strong El Nino event of 1997–1998 (Figs. 2A, B).

Fig. 5. Average fluxes of dust components at northern vs. southern sites compared to categories of yearly precipitation (YP), previous yearly precipitation (PYP), unusual winter-precipitation events of the same (WE) and previous (PWE) years, and unusual summer-precipitation events of the same (SE) and previous (PSE) years. Categories of precipitation are evenly divided among entire range of values for the dataset, except that event category 0 indicates that no unusual event occurred, not that there was no precipitation. Letters designate categories within area groups with statistically different populations based on non-parametric tests; combined letters indicate population of category overlaps with two other categories. (A) Silt-clay flux; (B) clay flux, (C) carbonate flux; (D) soluble-salt flux.

Nonparametric statistical tests confirm that silt-clay fluxes are higher in the southern part of the study area than in the northern part, whereas clay fluxes are only slightly higher in the south and fluxes of carbonate and soluble salt are equivalent (Fig. 5). Dust flux



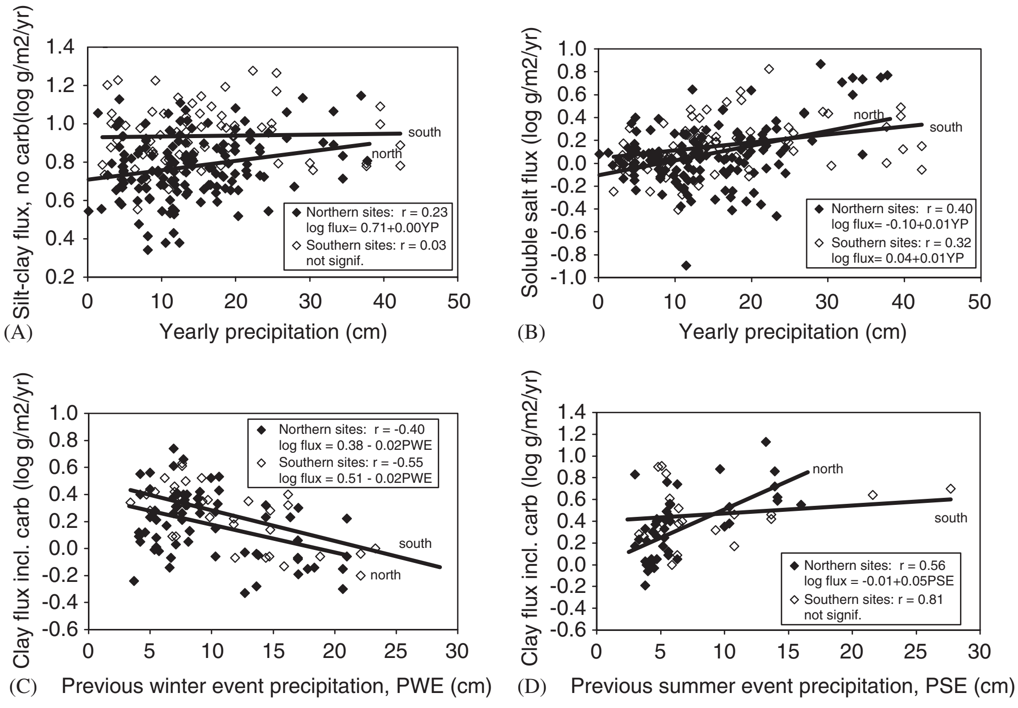


Fig. 6. Linear regression of components of dust flux ($\log_{10}$ values) with precipitation grouped by northern and southern areas. Abbreviations as in Fig. 5. (A) silt-clay flux with YP; (B) soluble-salt flux with YP; (C) clay flux with PWE; (D) clay flux with PSE.

components show consistent trends with some precipitation categories. The differences between categories are not always statistically significant (significant differences denoted by different letters within groups on Fig. 5) because the distributions of populations within adjacent categories frequently overlap. However, the consistent change in some populations with change in precipitation suggests that simple correlations of dust flux with some precipitation variables are likely to be significant. For the northern sites, the silt-clay flux generally increases with categories of increasing YP, WE, SE, and PSE, and decreases with increasing PWE (Fig. 5A). For the southern sites, silt-clay flux shows no consistent increases with precipitation categories, but like the northern sites it decreases with increasing PYP and PWE. Clay flux has similar patterns with climate variables and it increases dramatically with moderate to large SE. Soluble-salt fluxes show consistent patterns of increases and decreases with precipitation categories that are very similar to those of the silt-clay fluxes, with the exception of the change in salt flux with PSE (Fig. 5D). For PSE in both parts of the study area, salt flux is highest with intermediate events (category 1) rather than with the largest events (category 2). In contrast, carbonate fluxes show few consistent or significant changes with precipitation categories, except decreases with PYP and PWE at southern sites and an increase with PSE at northern sites (Fig. 5B).

Correlations of dust flux with climate variables also show different patterns for sites in the northern vs. southern areas (Table 1, Fig. 6). Correlation coefficients are low ($r < 0.50$) and show only small improvement when all data are used (Table 1). At northern sites, correlations of silt-clay and soluble-salt fluxes (positive) and carbonate flux (negative) with

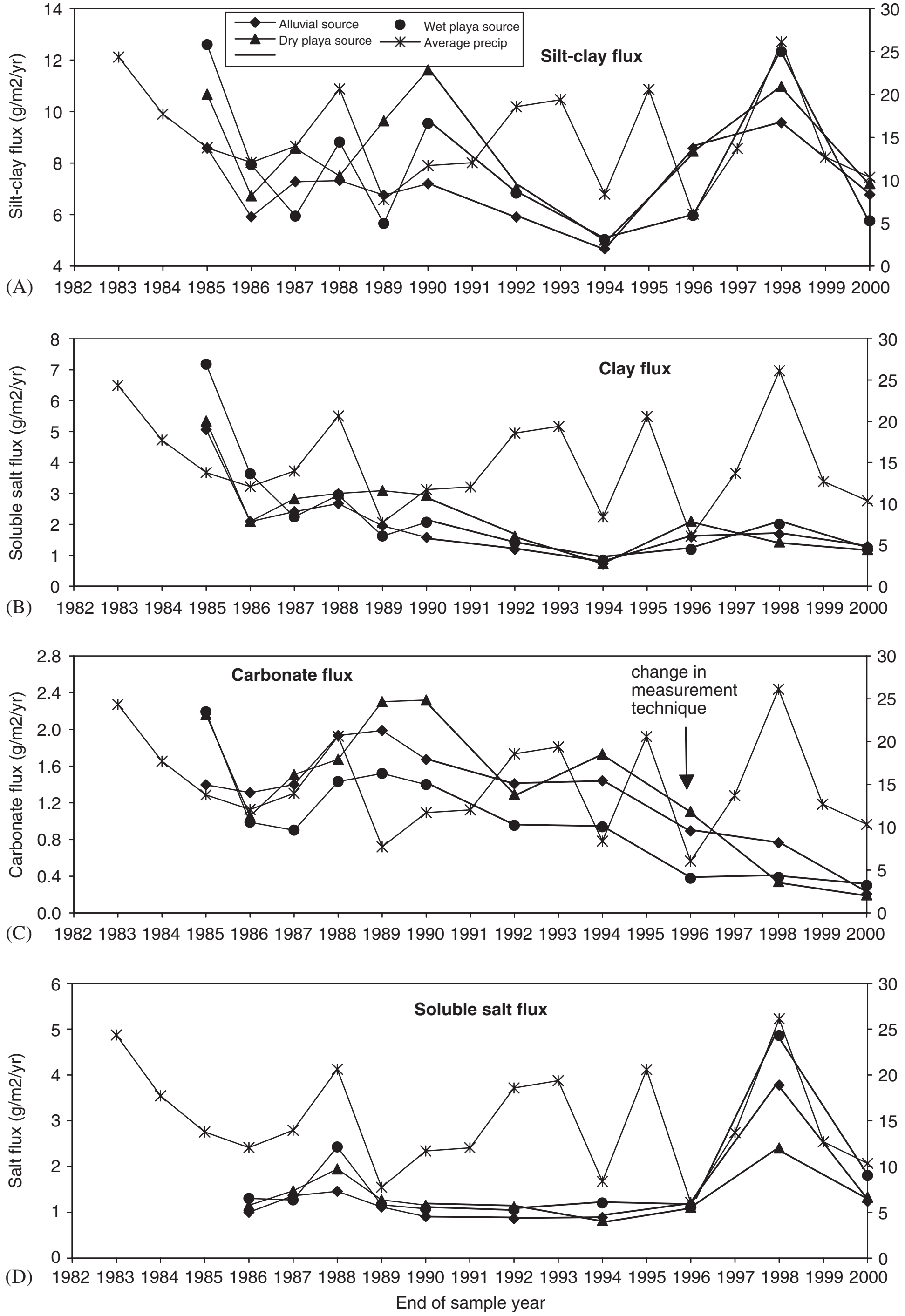


Fig. 7. Average precipitation compared to average fluxes of dust components grouped by primary dust source (see Appendix A for source assignments). (A) Silt-clay flux; (B) clay flux; (C) carbonate flux (arrow indicates change in method of carbonate analysis); (D) soluble-salt flux.

YP are significant and somewhat improved over the correlations performed using all sites (Figs. 6A, B). Clay flux increases significantly with PSE (Fig. 6D). In contrast, at southern sites only soluble-salt flux is positively correlated with YP, and flux components are negatively correlated with PYP and with PWE (Fig. 6C). Together with the results of the nonparametric statistical comparison using categories just described (Fig. 5), the correlations suggest that regional variations in vegetation response to precipitation do influence rates of dust accumulation but do not produce large differences in dust flux between the northern and southern parts of the study area.

3.2. Dust flux vs. dust source types

Comparison of average dust flux grouped according to the primary type of source (<20 km upwind) shows characteristic patterns related to precipitation. The silt-clay and carbonate fluxes exhibit similar trends (Figs. 7A, C). The clay fluxes also have similar trends (Fig. 7B), except that the very high clay fluxes in 1984–1985 do not re-occur in later years. At sites with alluvial and dry-playa sources, these fluxes show increases with successive dry years and lesser increases with very wet years, whereas the fluxes at sites with wet-playa sources decrease during most dry years and peak sharply during wet years. Carbonate flux appears to be highest near dry playas and lowest near wet playas. In contrast, soluble-salt flux appears to increase only during years of abnormally high precipitation (Fig. 7D), and is highest near wet playas. Several years of moderate precipitation seem to suppress dust fluxes from all three source types.

Nonparametric statistical tests confirm that dust flux components respond differently to precipitation change at sites with different primary dust sources. Silt-clay and clay fluxes are similar in amount among the three source types (Figs. 8A, B), but differ with precipitation categories. All types of sites show increases in the silt-clay and clay fluxes with increasing PSE, wet-playa sites especially, and show decreases with PWE. Sites with alluvial and dry-playa sources show little change in silt-clay flux with YP and WE. Wet playas produce the most dust following a wet year preceded by a strong summer event. Carbonate flux is highest at sites near alluvial and dry-playa sources (Fig. 8C). Carbonate flux appears to be most suppressed by high YP and PYP as well as high PWE and is enhanced by higher PSE, especially for sites with wet-playa sources. Soluble-salt flux consistently increases with YP, WE, and SE. However, the largest summer precipitation events appear to suppress salt flux at sites near wet playas; these sites record the highest salt fluxes in years with largeWEs and moderate summer events in the sample year and in the previous year.

Correlations of dust flux with climate variables at sites grouped by primary source show significant improvement in correlation coefficients for some climate variables compared to the correlations using all data (Table 1, Fig. 9). Correlations of soluble-salt flux are positive with YP for all source types (Fig. 9A); the silt-clay flux is also positive with YP and PSE for sites near wet playas (Fig. 9B and Table 1). Correlations of carbonate flux with YP, PYP, and PWE are negative for sites near alluvial and dry-playa sources, and are not significant for wet-playa sources (Fig. 9B). Clay flux is negatively correlated with PWE for all source types, and is positively correlated with PSE (Figs. 9C, D). Silt-clay flux is correlated with salt flux at sites near alluvial sources ($r^2 = 0.25$) and especially near wet playas ($r^2 = 0.44$); carbonate flux is less well correlated with silt-clay flux and especially

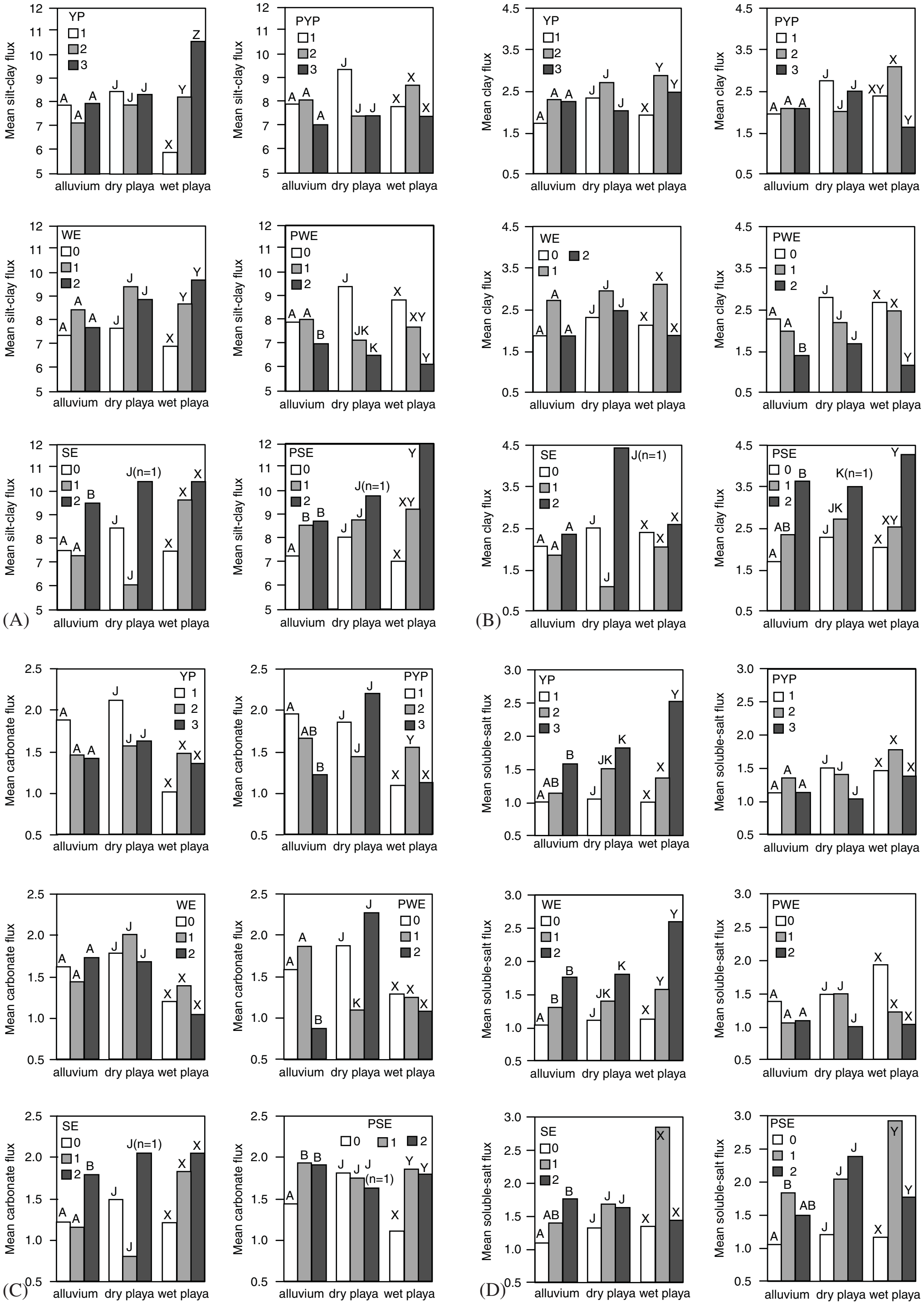


Fig. 8. Average fluxes of dust components at sites with different primary sources compared to precipitation categories (see Fig. 5 for definitions of categories and letter groups). (A) silt-clay flux; (B) clay flux, (C) carbonate flux; (D) soluble-salt flux.

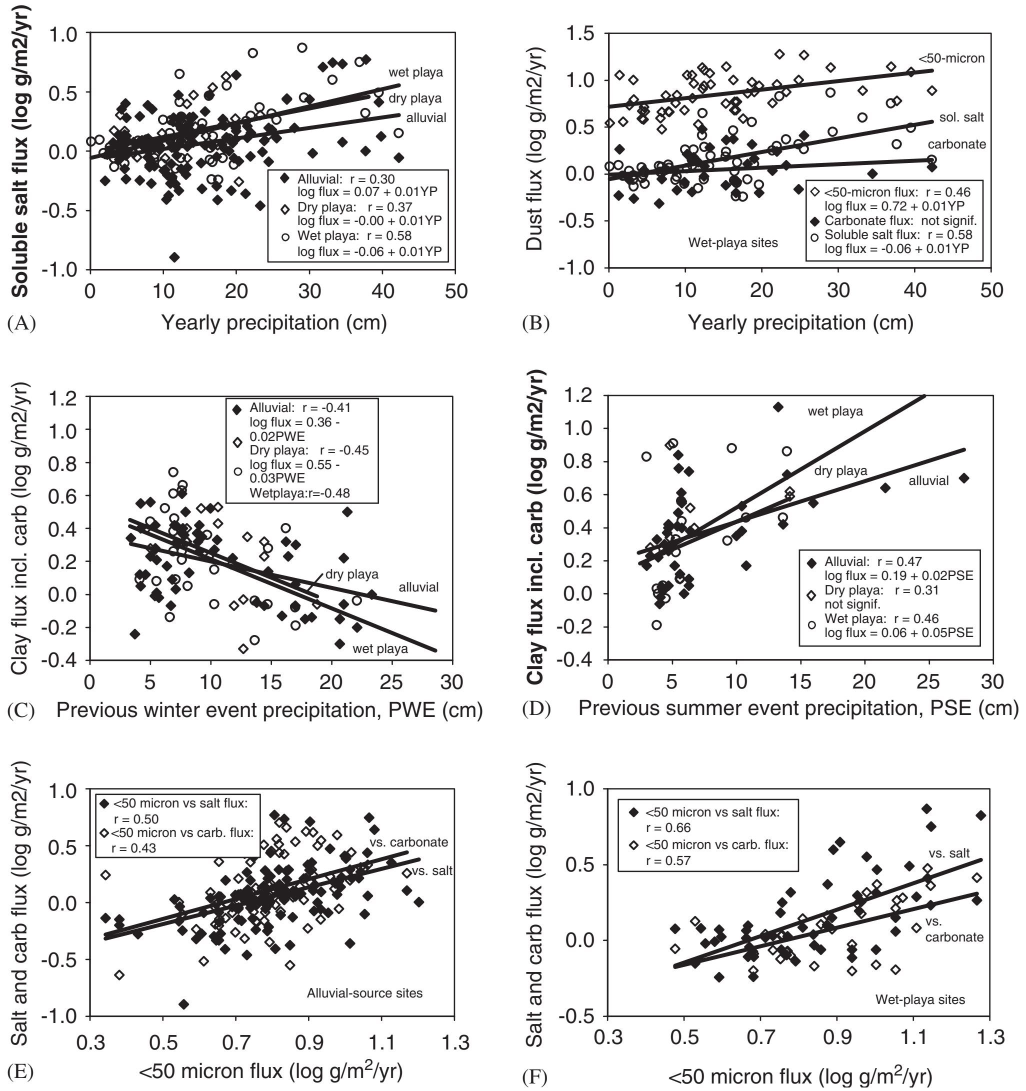


Fig. 9. Linear regression of components of dust flux ($\log_{10}$ values) with precipitation grouped by primary source. (A) soluble-salt flux with YP; (B) silt-clay, carbonate, and soluble-salt flux at sites near wet playas with YP; (C) clay flux with PWE; (D) clay flux with PSE; (E) relations of salt flux with silt-clay flux at sites with alluvial sources and wet-playa sources.

with soluble-salt flux for all source types (Figs. 9C, D). Clay flux is much less closely related to salt flux than is silt-clay flux (Table 1), implying that the behavior of clay particles may be decoupled from that of silt-sized sediment. Although wet playas seem to produce more of all three dust components with summer precipitation events in the year preceding collection (PSE, Fig. 8), only the correlation with silt-clay and clay flux is statistically significant, due to the apparent suppression of carbonate and soluble-salt flux by the strongest summer events. Together with the results of the nonparametric statistical comparison using categories (Fig. 8), the correlations show that different source types respond differently to changes in precipitation.

4. Discussion

Dust entrainment and deposition are affected by many factors. Dust entrainment depends chiefly on (1) daily and seasonal meteorological conditions that can generate turbulent winds capable of raising dust (Goudie and Middleton, 1992); (2) the threshold friction velocities of surface materials (Gillette et al., 1982; Gillette and Sinclair, 1990), which are mainly dependent on particle size and moisture content and also on clay mineralogy and degree of cementation or crusting of the source (Potter, 1990); and (3) the type and amount of vegetation (Musick and Gillette, 1990; Musick, 1999). These three parameters fluctuate both annually and seasonally. Dust accumulation mainly depends on rate of supply from the source(s), variable wind speed, rainout of dust in transport, and air turbulence caused by topographic variations (Goossens, 1988) and vegetation cover and height. Thus, annual changes in the amount and seasonal distribution of precipitation, modulated by vegetation growth or die-off and by change in the physical and chemical state of surface sediments, should be important controls on dust accumulation rates.

Although regional drought is known to be a primary cause of dust storms (summarized by Pye, 1987), most researchers who studied the role of drought in dust generation found low correlation coefficients with much unexplained variability (e.g. Chepil et al., 1963; Yu et al., 1992). Brazel and Nickling (1987) attributed some of this variability to control of dust-storm generation by vegetative cover, surface crusting, and surface disturbance. Studies in the southwestern United States have found a negative correlation between dust emission and degree of vegetative cover; vegetation, in turn, is related to the preceding fall and winter rainfall (Mackinnon et al., 1990; Musick and Gillette, 1990; Musick, 1999). The present study illuminates many of the complex interactions of the factors affecting dust generation and accumulation downwind by separating dust into four components—silt-clay, clay, carbonate, and soluble salts—and examining their interaction relative to nearby dust sources and patterns of precipitation. These observations confirm and expand upon interpretations of a previously published study (Reheis and Kihl, 1995) that used a portion of the current dataset.

4.1. The role of wind

The seasonality and strength of surface winds are important to the generation of dust (Chepil et al., 1963; Brazel and Nickling, 1986; Gillette and Hanson, 1989; Helm and Breed, 1999; Stout, 2001) and to rates of dust deposition (Smith et al., 1970; Goossens, 2001). Wind energy is high throughout the region; although threshold velocities near the study sites were not measured, the seasonally high wind speeds between March and June are easily capable of sediment erosion and transport (Fig. 10C; data from http://ingrid.ldeo.columbia.edu/). Maximum daily average values typically are about two times faster than the monthly average values at each station and the two parameters are closely correlated.

The dust-trap collection intervals are 1–2 years, yet large wind events during these periods are likely to be responsible for much of the dust flux. To evaluate the effects of such large events, the five largest mean daily winds and the five largest daily peak gusts

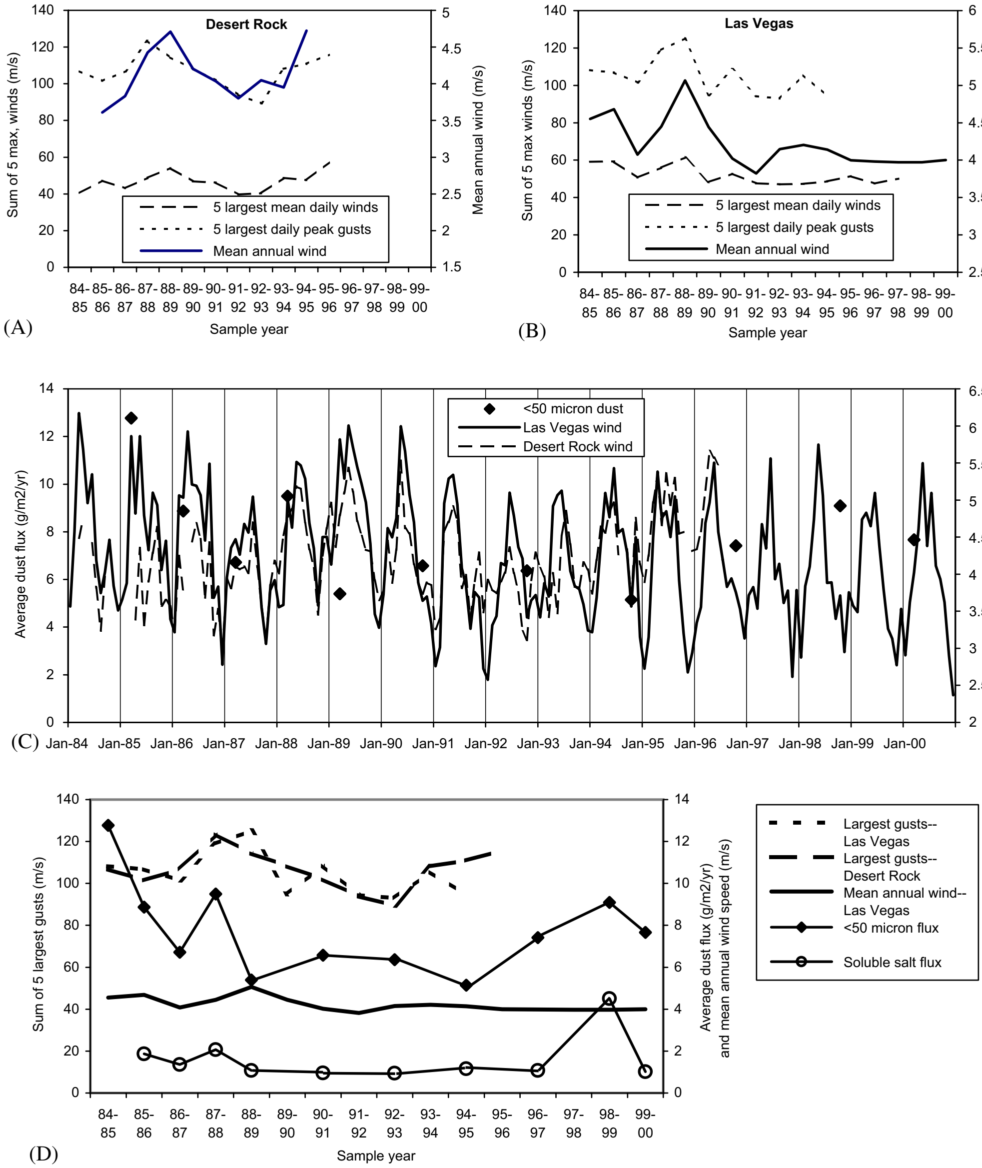


Fig. 10. Wind data (http://ingrid.ldeo.columbia.edu/) compared to dust flux in the study area. (A,B) comparisons of mean annual wind speed and sums of five largest mean daily winds and five largest daily peak gusts (proxies for significant erosive wind energy) at Desert Rock (Nevada Test Site) and Las Vegas, Nev. (C) Average yearly dust flux at sites T11, T13, T14, and T15 compared to mean monthly wind speed at nearest locations. (D) Average yearly dust flux compared to mean annual wind and five largest daily peak gusts at same sites.

during a sampled year were summed and compared to mean annual wind velocities (Figs. 10A and B). Generally, these parameters correspond although annual fluctuations are rarely of the same magnitude. As might be expected, peak gusts are more independent of mean annual winds than are maximum mean daily winds.

The annual and monthly average wind speeds show changes that are poorly correlated with dust flux over time (Figs. 10C, D). For example, the highest average annual wind speed for Las Vegas occurred in 1988–1989 when silt-clay dust flux at nearby sites decreased sharply. The following period of low average wind speeds coincides with a peak in dust flux in 1989–1991. Some periods of relatively high silt-clay flux do correspond with one or more months of above-average winds (e.g. 1984–1985, Fig. 10C). However, in other sampling periods the dust flux decreased sharply despite equally high winds (e.g. 1985–1986).

The measures of effective wind energy, including summed largest gusts and largest daily winds, also do not correspond well with dust flux (Fig. 10D). However, large wind events recorded at Las Vegas and Desert Rock in 1987–1988 do coincide with a peak in silt-clay flux at local dust-trap sites (but not regionally; compare with Fig. 4). Thus, it appears that annual and monthly variations in average wind velocity are not a primary control of dust flux, but unusually gusty winds locally may affect dust flux even in relatively wet years like 1987–1988 (Figs. 2 and 4). This inference is similar to findings of Okin and Reheis (2002) that ENSO anomalies in the desert Southwest are uncorrelated with wind speed.

4.2. *The role of precipitation*

Changes in threshold friction velocities and vegetation (percent cover) are controlled in part by rainfall, assuming that human effects are negligible or at least constant (Goudie and Middleton, 1992; Lee et al., 1993). These changes in thresholds are expected to differ among dust-source types. Increases in precipitation can encourage growth of annual vegetation, especially on well-drained alluvial surfaces, and thus inhibit local dust generation by increasing the threshold friction velocity (Holcombe et al., 1987; Musick and Gillette, 1990; Stockton and Gillette, 1990). Many studies worldwide have noted the correlation between drought, consequent reduction in vegetation cover, and increased frequency of dust storms and dust deposition downwind (e.g. Goudie, 1978; Young and Evans, 1986; Mackinnon et al., 1990; McTainsh et al., 1998; Prospero and Lamb, 2003). On the other hand, large runoff events from major storms, especially in summer months, can deliver fresh sediment that is easily deflated from depositional areas such as dry playas (Gillette et al., 1980; Marticorena et al., 1997; McTainsh et al., 1999; Mahowald et al., 2003). Wet years or wet winters can produce surface salt efflorescence on playas with surfaces above the water table, destabilizing the surface crusts and enhancing susceptibility to deflation, as documented for Owens (dry) Lake (Barone et al., 1979; Saint Amand et al., 1986; Reid et al., 1994; Gill, 1996; Tyler et al., 1997).

Groups of sites in the northern and southern parts of the study area serve as a proxy for average mean annual temperature and potential evapotranspiration, which increase from north to south, and to a lesser extent for seasonality and sources of precipitation. The average silt-clay and clay fluxes are higher at southern sites than at northern sites (Figs. 4, 5A, and B), due in part to higher mean annual temperature to the south (Reheis and Kihl, 1995), and perhaps also to increased moisture to the north during the spring growing season when evapotranspiration is low (Fig. 3). The average carbonate flux is slightly higher in the northern than in the southern sites (Fig. 5C). As shown by Reheis and Kihl (1995), this is likely due to the concentration of northern sites that are located on alluvial fans derived from calcareous rocks (these include T-15, T-16, T-18, and T-47–49, as well as neighboring sites that are partly influenced by calcareous alluvial sediments; Fig. 1). Thus, higher carbonate flux is probably not climate-related. There is no obvious difference in soluble-salt flux between the two parts of the study area.

Sites throughout the study area show high silt-clay and soluble-salt fluxes in years with exceptionally high rainfall and lower fluxes in years with moderate rainfall (Figs. 2 and 4). Silt-clay flux at southern sites was also high in 1989–1991, coinciding with several years of drought. The sharp increases in silt-clay and salt fluxes in 1997–1999 may not be simultaneous with the high rainfall in 1997–1998 because the samples represent the integration of 2 years of dust accumulation. However, dust samples collected seasonally from high-altitude snowpacks and from collection plates at three localities near Soda Lake suggest that dust flux in 1998 in the Mojave Desert was at least double the flux in subsequent years (T. Hinkley, US Geol. Survey, written commun., 2004), supporting the interpretation that increases in dust flux can correspond to large wetting events as well as to lengthy droughts. Samples collected seasonally during the last 5 years from the study area (partial data in Reheis, 2003) also show higher amounts of soluble salt in the winter (November–April) when effective moisture in surface sediments is higher than in summer (June–October). Furthermore, minor increases in silt-clay and soluble salt fluxes coincided with a moderate El Nino event in 1987–1988 when samples were collected annually (Figs. 2 and 4). These observations suggest that increased dust flux accompanies years of high rainfall as well as lengthy droughts. Statistical analyses also indicate consistent trends in dust flux components with some precipitation categories (Table 1, Figs. 5 and 6), including large seasonal precipitation events.

These results can be interpreted in terms of vegetation response to seasonal precipitation. Although average winter precipitation amounts are similar for northern and southern sites (Fig. 3), winter precipitation in normal years may be less effective in the south where average potential evapotranspiration is higher due to lower altitudes and latitudes. Okin and Reheis (2002) found a significant negative correlation with a 1-year lag between dust events (sustained wind erosion events) and the preceding December–January–February ENSO anomaly and precipitation for an area overlapping the southern part of the present study area. Brazel and Nickling (1986) also noted correspondence between variability of dust events and antecedent winter moisture in southern Arizona. They attributed the 1-year lag to the protective effects of senescent grasses and other annual plants that grow in response to high precipitation in the winter and spring (Holcombe et al., 1996; Helm and Breed, 1999; Musick, 1999). Such periods in the southern deserts typically occur only during El Nino years. A negative correlation with a 1-year lag is consistent with observations in this paper that dust deposition at southern sites increases with drought years (Figs. 2B, D and 4C) and is negatively correlated with precipitation of the previous year (PYP, Table 1). In contrast, northern sites show much less consistent response to drought years (Figs. 2A, 4B), probably due to greater vegetative cover at many of the sites and to more effective winter moisture. Both areas show consistent decreases in dust flux with WEs during the previous year (PWE, Table 1, Figs. 5 and 6), emphasizing the importance of winter–spring precipitation in enhancing vegetation growth and the prolonged stabilizing effects of this vegetation relative to wind erosion susceptibility.

At the northern sites, rapid responses of dust production and accumulation to high rainfall, and especially to summer flooding, may in part result from the increased delivery or reworking of alluvial and playa sediment by storm events. Northern sites show increases in dust flux with increasing precipitation during the sample year (Table 1, Fig. 6), and for clay and carbonate, with summer event precipitation (YP and SE, Table 1 and Figs. 5

and 6). Okin and Reheis (2002) also found anomalous increases in dust event frequency with the strongest El Nino years.

4.3. The role of dust source

Many studies have found that both alluvial plains and playas can act as dust sources (e.g. Pye, 1987; Reheis and Kihl, 1995; McTainsh et al., 1999). Gillette et al. (1980) proposed that in the southwestern US under present climate, alluvial deposits are larger dust sources than playas. Reheis and Kihl (1995) pointed out that though both sources produce similar amounts of dust, the much larger area of susceptible alluvial deposits means that the potential contribution of modern dust from alluvium is greater than that from playas. Abundant production of dust from playa surfaces and increased accumulation downwind of such sources has been documented in many previous studies (e.g. Young and Evans, 1986; Blank et al., 1999; McTainsh et al., 1999; Mahowald et al., 2003).

Studies of dust generation and dust deposition to date have not noted the essential differences between (1) dry playas that respond by emitting dust in dry periods after major storm events deliver fresh sediment and (or) destabilize the surface crust, and (2) wet playas that emit dust as a response to capillary rise and surface evaporation. Such near-surface phenomena can be affected by local wet or dry years as well as by long-term precipitation change in the groundwater source area (assuming no change due to groundwater withdrawals).

Some workers have made observations relevant to the distinction between wet and dry playas. Young and Evans (1986) used ground-level collectors in a high-altitude valley in central Nevada to monitor dust from a playa, and found that dust accumulation was highest in winter months and varied inversely with annual precipitation. They also noted that salt-rich dust plumes commonly arose from a small area of the playa that had puffy, salt-crusted sediment and was continually moist from capillary rise of shallow groundwater. Blank et al. (1999) reported extraordinarily large amounts of saline dust deposited in ground-level collectors on and downwind of a wet playa in western Nevada during 2 years of normal to very high precipitation following several years of drought. R. Forester (US Geol. Survey, 2004, written and oral communs.) proposes that salt-rich dust emission from wet playas can be a rapid response to wetting events. Reheis and Kihl (1995) did not differentiate between dry playas and wet playas, but their results suggested that some playas behaved quite differently than others by noting that "downwind from most playas, pulses of dust deposition occur in a dry year that follows a wet year; and…downwind of many alluvial sources and some playas, pulses of dust deposition occur during a wet year." This study also noted that many sites had peaks in dust flux in 1984–1985 following large summer storms that wetted playa surfaces and generated floods and debris flows throughout the region of southern Nevada and adjacent parts of California (Fig. 2, Appendix A). Such areas of disturbed ground could produce large amounts of dust as soon as surfaces dried (Gillette et al., 1982; Yaalon and Ganor, 1973).

The components of dust flux measured in this study are strongly related to the type of dust source as well as to the amount and seasonal distribution and intensity of precipitation. Judging from the improvement in correlation coefficients of dust flux with climate variables, source type appears to be more important than average regional climate as a factor in dust production (Table 1, Fig. 9). Wet playas appear to be the most volatile dust sources and produce the most dust (silt-clay, clay, and salt) following a wet year preceded by a moderate to strong summer event (PSE, Figs. 7 and 8) and the least dust during dry years.

These changes in dust flux can be understood in terms of how different sources respond to changes in the amount, seasonal distribution, and intensity of precipitation. Vegetation in general is far more abundant on alluvial plains and distal alluvial fans than on playas because alluvial deposits are well drained and typically not highly alkaline or saline, unlike most playas. Seemingly barren alluvial fans can produce extravagant growth and flowering of annual plants after soaking rains, especially in late winter and spring when evaporation rates are relatively low. As a result, the growth, senescence, and die-off of vegetation in response to annual and decadal precipitation cycles play a significant role in inhibiting or exacerbating dust production from alluvial sources (Peters and Eve, 1995; Reheis, 1997; Helm and Breed, 1999).

The lag induced by vegetation is apparent in the negative relation of silt-clay and clay fluxes with previous winter precipitation events at sites with alluvial sources (Figs. 8A, 9C). Carbonate flux near alluvial and dry-playa sources is even more strongly depressed by increasing PWE and in general by increasing moisture in either the current or previous years (Fig. 8C, Table 1). Carbonate flux is well correlated with silt-clay flux at sites with alluvial sources (Fig. 9E), and its behavior probably is also affected by dissolution and leaching below the ground surface during cooler winter-event precipitation as well as by vegetation growth. Moderate to large summer precipitation events enhance production of silt, clay, and carbonate dust from alluvial sources during either the current or previous years. Because summer storms produce rapid runoff and increase fluvial sediment transport (Yair and Kossovsky, 2002; Etheredge et al., 2004), increased dust flux is likely caused by fresh sediment, unvegetated and uncrusted, deposited on alluvial fans by such floods.

Dry playas in the study area, with hard silt-clay surfaces and relatively deep water tables, behave similarly to alluvial sources in that they produce more silt and clay dust in response to summer storms and less silt, clay, and carbonate dust after previous winter precipitation events (Figs. 9C, D). Like alluvial sources, they also produce larger amounts of carbonate-rich dust during longer periods of drought (Fig. 7). Summer flood events may deliver fresh sediment to playa margins and surfaces, and if large enough to wet the playa floor, may destabilize the hard-packed surface by creating mud-cracked surfaces that deflate easily as the playa dries. Such responses were suggested in the earlier study by Reheis and Kihl (1995), mainly based on the high fluxes of clay and carbonate downwind of playas after the large summer storms of 1984. Other studies have also suggested increased dust generation from playas as a response to drying after flood events deliver fresh sediment (McTainsh et al., 1999; Mahowald et al., 2003).

In general, sites near dry-playa sources seem to have more variable dust flux. This variability could arise from several causes. First, the localized nature of summer storm events means that a storm recorded at a weather station may not have affected a nearby playa. Second, many playas exhibit behavior transitional between truly “dry” playas and truly “wet” playas. For example, a series of wet years could raise water table or mobilize subsurface salts beneath a dry playa such that it temporarily responds more like a wet playa. Such a case may be represented by the notable increase in silt-clay and salt fluxes in 1997–1999 at site T-26, downwind of Ford Dry Lake (Figs. 1 and 2D). Also, small areas on the margins of dry playas may be affected by locally shallow, perched water tables such that those areas respond more like wet playas.

Wet playas in southern Nevada and California appear to be volatile, "point" sources of dust that respond to increases in annual precipitation and to summer storms in the previous year by emitting increasing amounts of silt, clay, and soluble salt (Figs. 7 and 8, Table 1). These responses are consistent with the concept that direct surface wetting as well as groundwater recharge may enhance the subsequent evaporative concentration of salts at and just below the surface, and this in turn likely will increase the susceptibility to wind erosion as long as the water table remains below the surface (playas with water tables at or above the surface will precipitate bedded salts that are wind-resistant; Rosen, 1994). These processes are probably governed by the chemistry of the brine and seasonal temperature and moisture changes (Eugster and Smith, 1965). Rapid evaporation of moisture following a summer storm would tend to concentrate soluble salts at the playa surface. However, on some wet playas, salt crusts that form at high summer temperatures form hard stable crusts that are not easily eroded; thus, the following cool winter temperatures, combined with sufficient moisture to re-wet the surface sediments, serve to hydrate the salts and create a fluffy, wind-erodible surface (e.g. Owens Lake; St. Amand et al., 1986). Because the dust samples in the present study were mostly collected in the fall, 1-year samples from sites near wet playas are probably recording dust produced as a response to previous winter and spring precipitation, and a smaller amount of dust that may be produced in response to moderate summer wetting events. These conclusions are consistent with results of a few other studies on seasonal wind erosion of wet playas in the southwestern US (Young and Evans, 1986; Cahill et al., 1996; Reheis, 1997).

Soluble salt flux increases with annual precipitation for all source types, but by far the highest correlation coefficient is that of soluble salt at sites near wet playas (Table 1, Fig. 9A). It is unclear whether soluble salts are actually produced by wind erosion of dry playas and alluvium or, given the poorer correlations, that sites nearest these sources are also receiving salt-rich dust from wet playas. The results may be somewhat confounded by the assignment of sites to only one primary dust source; as noted above, most sites assigned to playa sources also have alluvial fans upwind. Wet playas are about equally distributed through the study area (Fig. 1), which may account for the close similarity in soluble salt flux at northern and southern sites (Figs. 4 and 5D). Playa-derived airborne salts may stay aloft either as suspended particles or as solutes in water vapor for considerable distances. Although the coarser-grained salt particles in dust plumes from Owens Lake are largely deposited within about 40 km of the lake bed (Mackinnon et al., 1996), soluble salt contents of dust samples taken at this distance are still higher than the regional average (Reheis, 1997). Contents of arsenic and antimony in dust samples indicate that dust from Owens Lake is being transported at least 400 km to the east (Reheis et al., 2002). In contrast, elemental data from dust samples collected along a transect eastward from Death Valley showed that strontium, presumably associated with calcium in carbonate minerals derived from playa-margin sediment, decreased to background levels within about 10 km from the playa (Reheis et al., 2002).

Long-distance transport of salts is supported in this study by high salt contents in 1997–1999 samples at sites T1–5, T15, and T16 about 50–70 km from the nearest wet playas (Appendix A, Fig. 1). In addition, sites at relatively high altitudes in montane settings as much as 150 km from wet-playa sources, including T7–7A, T37, T44, and T45, show much larger salt fluxes in 1997–1999 (Reheis, 2003). These abnormally high accumulation rates at high-altitude sites suggest that soluble salts in part are transported in solution, and are rained out when air masses encounter mountain ranges as suggested by Reheis and Kihl (1995). It is also possible that salts originating from wet-playa sources are widely distributed by dry deposition and rainout, thus being incorporated into alluvial sediments and soils that in turn become less concentrated sources of salts in dust.

5. Conclusions

A 16-year record of modern dust flux in the southern Great Basin, Mojave Desert, and Sonoran Desert shows large fluctuations in the wind erosion and accumulation of silt-clay, carbonate, and soluble salts from several types of sources. Because wind energy in most years is sufficient to erode sediment from any susceptible source, these fluctuations are largely a response to annual- and decadal-scale changes in precipitation, modulated by vegetation growth in relatively wet winters and springs and locally by unusual wind events. Average fluxes of silt, clay, and carbonate are higher in the southern part of the study area than in the northern part primarily because the southern part has lower vegetation density and higher average temperatures and evaporation rates. Soluble-salt fluxes are about equally distributed regionally, though not locally. Fluxes of silt, clay, and carbonate typically increase during sequences of drought years and also as a response to summer storm events. Fluxes of silt, clay, and salt also increase sharply during abnormally wet years that coincide with strong El Nino events in 1987–1988 and especially in 1997–1998. These conclusions are generally consistent with those of Reheis and Kihl (1995) based on more collection sites but only a 5-year record.

Most importantly, the longer record combined with the recognition that playas behave differently as dust sources depending on their groundwater depths (R. Forester, written commun., 2004) provides critical information on the differing behavior of dust sources in response to climate change. Alluvial deposits are primary dust sources during lengthy drought periods, especially in the southern part of the study area, because vegetation cover decreases in drought conditions. Both alluvial and dry-playa sources also produce silt, clay, and carbonate dust in response to storm events that generate runoff and sediment transport. Such dust events are most likely in summer and fall when evapotranspiration rates are high, permitting newly deposited sediment to be deflated almost immediately. These sources are inhibited by years in which rainfall is high and comes mostly as less intense events during the winter and spring; carbonate flux is particularly depressed during such times. In contrast, wet playas become primary dust sources during high-rainfall years due to their near-surface concentrations of soluble salts that respond sensitively to surface wetting and groundwater fluctuations. Wet playas, and arid regions with near-surface groundwater, may be the primary sources of soluble salts in dust.

Dust generation and accumulation in the southwestern US is a complex response to both high and low rainfall. Dust-emission models suggest that the global dust load is primarily related to climate change and not a direct response to land-use change (Zhang et al., 2003; Tegen et al., 2004), but variable responses of different dust sources to the amount and seasonal distribution of precipitation observed in this study indicate that dust emissions may either decrease or increase in response to climate change. Careful assessments of the types and behaviors of dust sources prevalent in the world's largest dust-generation regions (Prospero et al., 2002) will be required to provide more refined input to models of predicted dust emission with climate change.

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Appendix A

Average yearly, winter, and summer event precipitation at weather stations nearest dust trap sites (Regional groupings follow weather stations; primary and secondary dust sources follow sites)

Year ending Sample interval	Average precipitation (cm)			Year ending Sample interval	Average precipitation (cm)		
	Yearly	Winter event*	Summer event*		Yearly	Winter event*	Summer event*
	Dyer (northern) Site T-61 (alluvium, high altitude)				*Tonopah and PM-1 (NTS)(northern) Sites T-43 + 44 + 45 + 46 (alluvium, high altitude)*		
1983	24.4	—	8.7	1983	32.4	11.8	12.5
1984	9.3	—	5.9	1984	24.6	—	16.0
1985	11.9	3.7	—	1985	13.8	—	6.3
1986	6.9	—	—	1986	11.2	—	—
1987	8.9	—	3.3	1987	21.0	—	5.5
1988	20.3	10.5	—	1988	23.3	5.4	—
1989	13.9	—	—	1989	10.5	—	—
1990	—	—	—	1990	15.8	—	5.8
1991	9.7	—	—	1991	15.4	6.7	—
1992	11.2	4.9	—	1992	14.2	8.8	—
1993	9.9	—	—	1993	11.6	—	—
1994	12.1	—	4.7	1994	11.6	—	—
1995	22.7	8.2	—	1995	19.8	5.7	4.1
1996	13.3	4.1	—	1996	6.8	—	—
1997	13.9	—	4.3	1997	18.8	7.2	—
1998	21.3	—	5.9	1998	31.3	8.8	7.3
1999	18.8	6.7	—	1999	20.7	6.8	7.4
2000	4.7	—	—	2000	18.3	6.8	—

	Goldfield and Tonopah (northern) Sites T-37 (dry playa, high alt. and T-42 (alluvium, high alt.)				*PM-1 (NTS)(northern) Site T-7+7A (alluvium, high altitude)*		
1983	21.9	8.6	6.7	1983	39.5	13.4	18.2
1984	19.3	—	10.4	1984	29.9	—	21.6
1985	13.3	—	6.1	1985	14.3	—	—
1986	10.7	—	—	1986	14.1	—	—
1987	17.4	4.2	5.8	1987	23.8	—	6.0
1988	23.3	9.0	—	1988	27.9	5.4	—
1989	11.5	—	—	1989	11.7	—	—
1990	11.3	—	—	1990	19.0	—	5.8
1991	13.7	5.4	—	1991	16.7	—	—
1992	13.3	5.8	—	1992	19.3	8.8	—
1993	10.0	—	—	1993	14.2	—	—
1994	11.8	—	—	1994	12.4	—	—
1995	22.9	9.1	4.7	1995	21.0	—	—
1996	7.8	—	—	1996	6.8	—	—
1997	14.6	—	—	1997	25.0	14.4	—
1998	26.9	8.7	8.0	1998	37.8	11.8	6.0
1999	14.7	5.1	—	1999	27.5	6.8	6.3
				2000	18.3	6.8	5.2
	Pahranagat NWR and Desert NWR (northern) Sites T-47+T-48 (alluvium) and T49-T50 (dry playa)				*Beatty (northern) Site T-35+36 (wet playa and alluvium)*		
1983	24.0	10.4	7.1	1983	28.0	16.0	6.9
1984	20.1	—	14.2	1984	8.9	—	10.0
1985	14.2	8.0	—	1985	13.2	7.1	—
1986	11.1	—	—	1986	10.9	—	—
1987	13.1	—	—	1987	16.4	5.0	—
1988	18.6	10.6	—	1988	23.2	—	—
1989	5.9	—	—	1989	6.9	—	—
1990	10.2	3.3	—	1990	12.4	—	4.4
1991	9.4	—	—	1991	11.1	5.5	—
1992	20.3	16.3	—	1992	16.6	11.1	—
1993	19.2	12.7	—	1993	17.3	—	—
1994	8.1	—	—	1994	7.9	—	—
1995	21.4	14.4	—	1995	23.7	17.0	—
1996	4.7	—	—	1996	6.9	—	—
1997	9.7	—	5.6	1997	18.6	—	4.2
1998	24.4	10.7	2.5	1998	36.9	16.2	4.2
1999	10.8	—	—	1999	12.5	—	—
2000	7.4	4.9	—	2000	17.2	6.1	4.1
	Amargosa Farms, Beatty, and 4Ja-n (NTS)(northern) Sites T11+13 (wet playa and alluvium); T14+15 (alluvium)				*Desert Rock and 4Ja-n (northern) Site T-1-5 and T-9 (alluvium)*		
1983	26.6	13.0	9.0	1983	28.4	9.8	11.8
1984	15.0	—	14.0	1984	21.9	—	16.5
1985	12.5	7.7	—	1985	15.4	7.8	—

1986	11.1	—	—	1986	15.7	—	3.0
1987	18.1	5.0	5.8	1987	19.9	—	4.4
1988	22.0	4.1	5.6	1988	21.5	—	—
1989	4.7	—	—	1989	4.9	—	—
1990	8.7	—	4.4	1990	9.5	—	—
1991	9.9	5.5	—	1991	11.7	—	—
1992	16.7	12.5	—	1992	17.3	13.0	—
1993	21.7	17.0	—	1993	26.5	20.7	—
1994	7.8	—	—	1994	8.3	—	—
1995	23.6	17.0	—	1995	27.7	21.0	—
1996	4.3	—	—	1996	3.9	—	—
1997	13.1	—	3.9	1997	12.3	—	4.7
1998	33.2	16.8	3.6	1998	34.5	19.3	3.4
1999	11.6	—	3.8	1999	13.9	4.6	—
2000	13.1	8.0	—	2000	12.4	8.9	—
	Pahrump, Amargosa Farms, Desert Rock, and 4Ja-n (northern)				*Death Valley (northern)*		
	Site T-10 (wet playa and alluvium)				*Site T-38+39 (wet playa)*		
1983	26.0	10.1	10.4	1983	11.6	6.6	2.9
1984	18.4	—	13.3	1984	5.5	—	3.0
1985	13.7	8.9	—	1985	1.4	—	—
1986	11.7	—	—	1986	2.7	—	—
1987	17.5	—	5.5	1987	4.5	—	—
1988	21.4	7.2	5.4	1988	16.3	8.1	4.3
1989	4.4	—	—	1989	0.1	—	—
1990	9.9	—	3.3	1990	3.3	—	—
1991	10.6	4.2	—	1991	2.7	—	—
1992	16.4	12.1	—	1992	6.6	5.8	—
1993	23.2	18.4	—	1993	8.9	7.3	—
1994	6.8	—	—	1994	1.3	—	—
1995	22.3	16.4	—	1995	8.0	6.6	—
1996	3.3	—	—	1996	1.9	—	—
1997	11.6	—	4.0	1997	6.9	—	3.8
1998	29.0	15.6	3.3	1998	12.3	7.8	—
1999	11.0	—	—	1999	3.1	—	—
2000	10.0	7.4	—	2000	2.4	—	—
	Desert National Wildlife Refuge and Las Vegas (northern)				*Shoshone and Pahrump (southern*		
	Sites T-16 and T-18 (alluvium)				*Sites T33+34 (wet playa)*		
1983	15.8	—	4.1	1983	21.0	11.6	6.8
1984	15.8	—	9.7	1984	12.4	—	5.8
1985	11.8	6.9	—	1985	12.2	10.0	—
1986	7.1	—	—	1986	8.9	—	—
1987	13.5	6.9	—	1987	15.3	—	—
1988	14.1	7.6	—	1988	18.7	10.3	—
1989	4.8	—	—	1989	7.4	—	—
1990	7.9	3.3	—	1990	10.3	—	5.1
1991	9.4	—	—	1991	11.8	6.4	—
1992	18.4	15.4	—	1992	19.0	13.0	—
1993	17.7	13.7	—	1993	21.8	17.8	—

1994	4.9	—	—	1994	4.6	—	—
1995	15.3	10.3	—	1995	17.9	13.8	—
1996	4.3	—	—	1996	3.2	—	—
1997	11.8	—	5.3	1997	10.2	—	4.7
1998	20.0	10.2	4.2	1998	22.3	12.8	—
1999	11.6	—	4.5	1999	9.4	—	—
2000	7.4	4.9	—	2000	8.3	4.7	—
	Searchlight (southern) *Site T-23 (alluvium)*				*Baker (southern)* *Site T-30+31 (dry playa)*		
1983	38.1	15.1	9.1	1983	17.1	8.8	5.0
1984	21.5	—	12.6	1984	9.3	—	5.3
1985	25.8	18.0	—	1985	7.4	3.9	—
1986	13.1	—	—	1986	10.6	—	—
1987	18.1	7.6	5.7	1987	9.8	—	—
1988	24.4	—	—	1988	19.8	9.2	6.4
1989	8.7	—	—	1989	5.1	—	—
1990	15.2	—	7.7	1990	9.2	—	—
1991	17.6	12.5	—	1991	6.9	—	—
1992	30.4	22.5	—	1992	15.8	12.1	—
1993	37.0	23.3	5.9	1993	12.9	11.9	—
1994	10.4	—	—	1994	2.3	—	—
1995	31.2	21.3	—	1995	—	—	—
1996	8.8	—	—	1996	—	—	—
1997	13.7	—	6.1	1997	13.1	—	4.8
1998	30.0	13.9	9.5	1998	16.7	10.2	—
1999	18.7	—	8.4	1999	6.1	—	—
2000	9.9	5.7	—	2000	3.4	—	—
	Mitchell Caverns and Mountain Pass (southern) *Site T-28 (alluvium) and T-29 (wet playa and alluvium)*				*Iron Mountain (southern)* *Site T-27 (alluvium)*		
1983	39.8	18.7	22.6	1983	14.4	8.2	2.9
1984	34.6	—	27.7	1984	9.0	—	5.1
1985	23.5	16.2	—	1985	12.0	6.2	—
1986	19.7	—	—	1986	12.4	—	3.7
1987	24.9	7.1	—	1987	8.5	—	—
1988	37.7	7.0	13.7	1988	11.4	—	—
1989	15.3	7.6	—	1989	3.1	—	—
1990	25.5	—	12.3	1990	4.0	—	—
1991	27.3	11.8	—	1991	11.2	—	—
1992	42.2	28.6	5.1	1992	18.0	12.6	—
1993	32.7	22.1	—	1993	18.3	14.7	—
1994	10.9	—	—	1994	6.8	—	—
1995	32.3	14.8	—	1995	12.1	9.7	—
1996	13.3	—	—	1996	2.0	—	—
1997	22.5	—	10.8	1997	9.2	—	5.7
1998	39.5	19.5	—	1998	18.1	10.0	—
1999	24.4	7.9	9.3	1999	6.8	—	—
2000	16.8	9.7	7.4				

	Iron Mountain and Parker (southern) Site T-25 (alluvium)				Blythe and Iron Mountain (southern) Site T-26+26A (dry playa and alluvium)		
1983	20.9	8.6	8.6	1983	13.6	5.7	3.3
1984	9.2	—	4.8	1984	9.8	—	5.5
1985	16.3	9.9	—	1985	14.1	7.9	—
1986	16.9	5.0	3.3	1986	13.0	—	—
1987	8.5	—	—	1987	7.1	—	—
1988	13.6	—	—	1988	13.2	3.4	—
1989	6.0	—	—	1989	3.3	—	—
1990	7.4	3.5	—	1990	4.1	—	—
1991	13.0	8.2	—	1991	10.1	—	—
1992	24.4	14.9	—	1992	14.4	8.3	2.4
1993	23.6	18.8	—	1993	18.4	15.9	—
1994	8.0	—	—	1994	6.4	—	—
1995	17.3	13.0	—	1995	11.4	9.3	—
1996	2.7	—	—	1996	4.0	—	—
1997	12.1	4.7	6.7	1997	10.1	—	6.4
1998	22.3	11.5	—	1998	18.6	10.9	3.6
1999	7.0	—	—	1999	8.1	—	—

*Winter event = Sum of precipitation during consecutive "unusual" months when precipitation in any 1 month from November through April equals or exceeds one-third MAP at a weather station. Summer event = Sum of precipitation during one or more "unusual" months when precipitation in any one month from June through October equals or exceeds one-half MAP at a weather station. Seasons with no unusual precipitation values are assigned a value of 0 (—).

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